TALC: A Simple C Language Extension For Improved Performance and Code Maintainability

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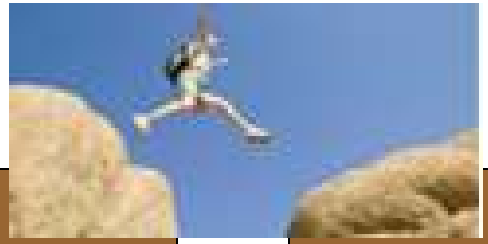
The Software Chasm



Many important HPC applications cannot be re-written for practical reasons:

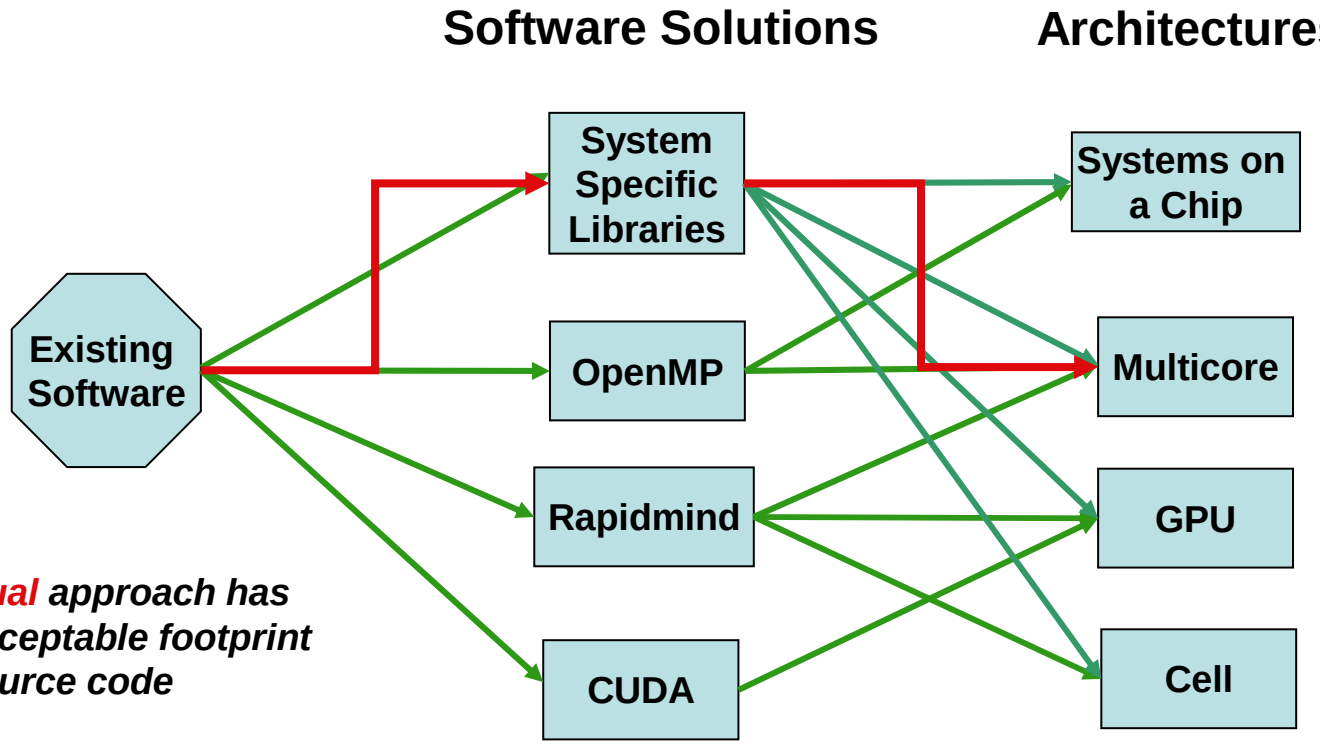
- Size of code.
- Additional efforts of validating a rewrite.
- What do you rewrite to?
- Impact on budget and deliverables.

Moore's law is now spurring a renaissance of architectural diversity in the HPC marketplace:

- Multicore (Intel, AMD, Sun, …)
- System on a chip (IBM BlueGene, SciCortex, …)
- The re-emergence of vector (Cray,ClearSpeed,Intel, …)
- Graphical Units to supplement work (IBM/Sony Cell, Nvidia, …)

What works well for one may work poorly for another.

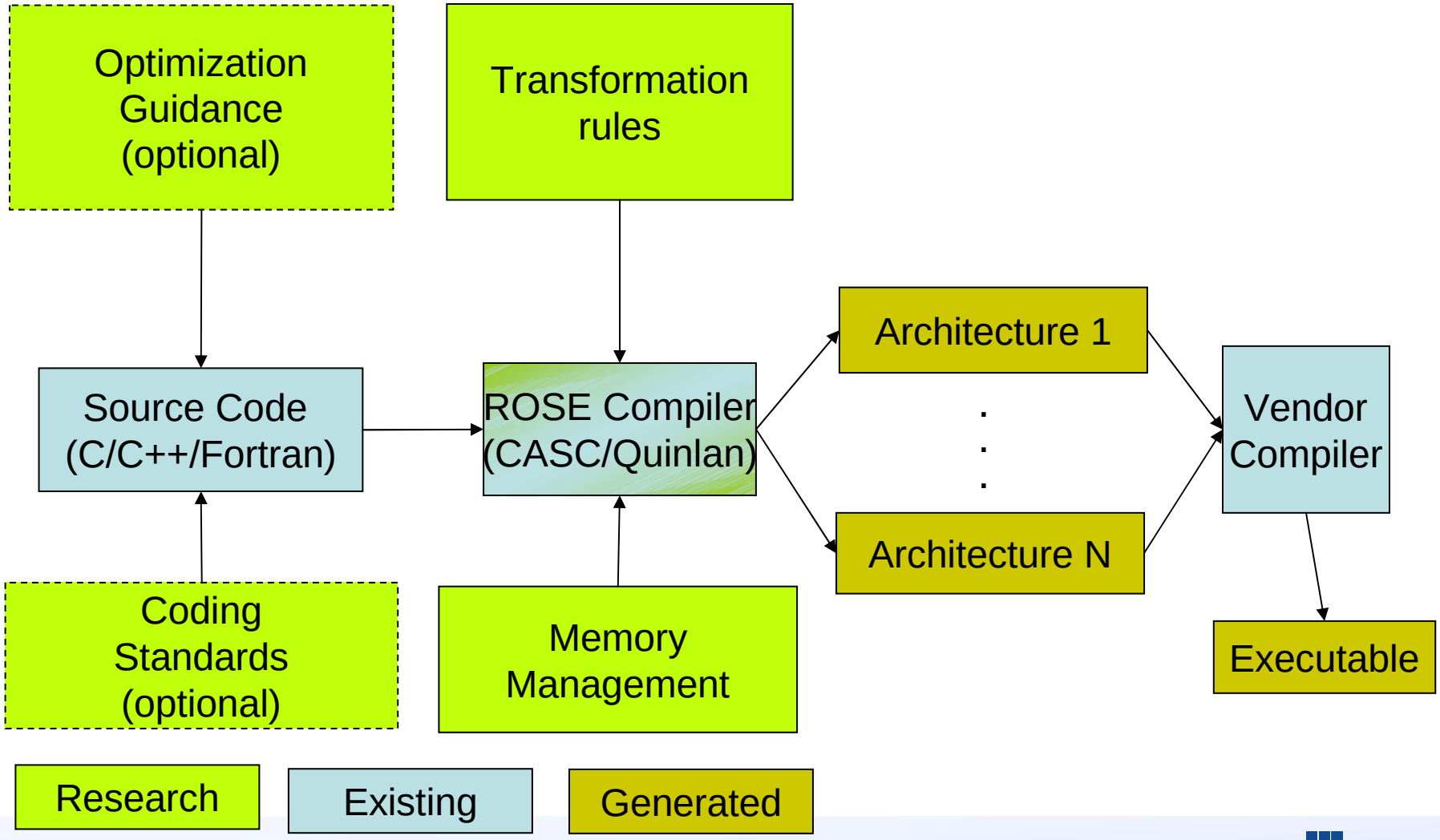
Many software options exist to port to new architectures



***Manual** approach has unacceptable footprint in source code*

- A *manual* rewrite would lock in one solution
- *Automated* transformations can generate each solution

We Would Like To Leverage a Single Source Code for Many Architectures



Motivation

- Many large science applications achieve a small fraction of peak performance

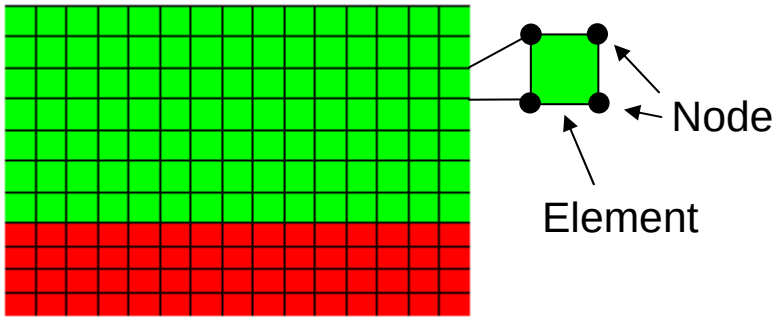
- Known roadblocks to performance include
  - User choice of data structures
  - Conservative optimization choices by compilers

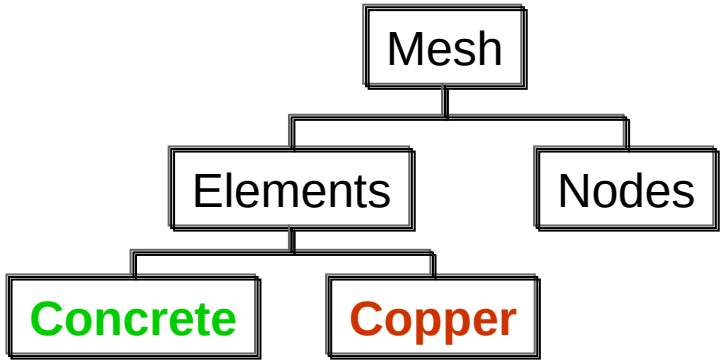
- We are working on a source-to-source translator called TALC to allow users to control these issues for mesh based codes without modifying their source code

Mesh Based Physics

- Meshes are used to solve partial differential equations
- Meshes are often described as a hierarchy of locality contexts
- Examples of contexts include: subdomains, patches, finite elements and material regions
- Data layout choices are often made within locality contexts to increase cache performance

2D Mesh

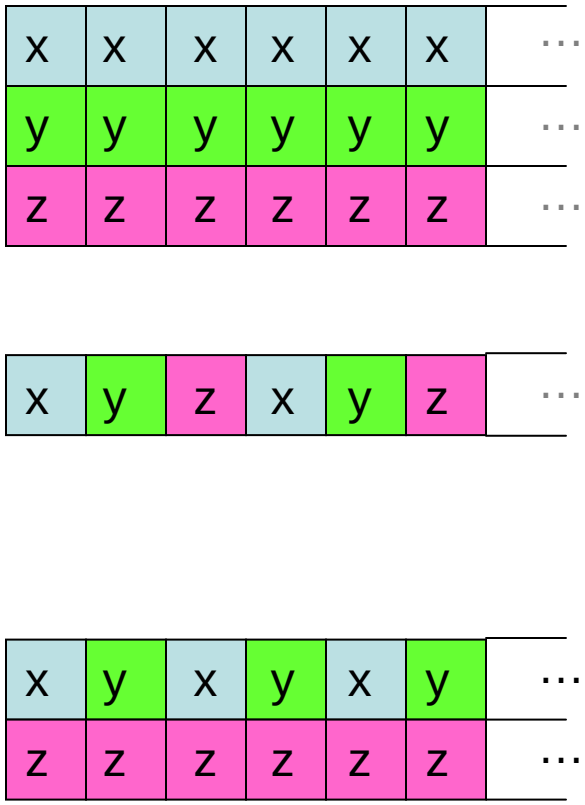




Fundamental Data Layouts

- Array-Like
  - ```
    double x[10000] ;
    double y[10000] ;
    double z[10000] ;
    ```
- Struct-Like
  - ```
    struct coord {
      double x, y, z ;
    } point[10000] ;
    ```
- Clustered-Struct
  - ```
    struct coord {
      double x, y ;
    } point[10000] ;
    double z[10000] ;
    ```

Memory Interleave


    ```

Stress-Strain Work Example – Array-Like Layout

```
double quarterDelta = 0.25 * deltaTime;

for (int i = 0 ; i < material_length ; i++){
  int index = material_map[i];
  double szz = - sxx[index] - syy[index] ;

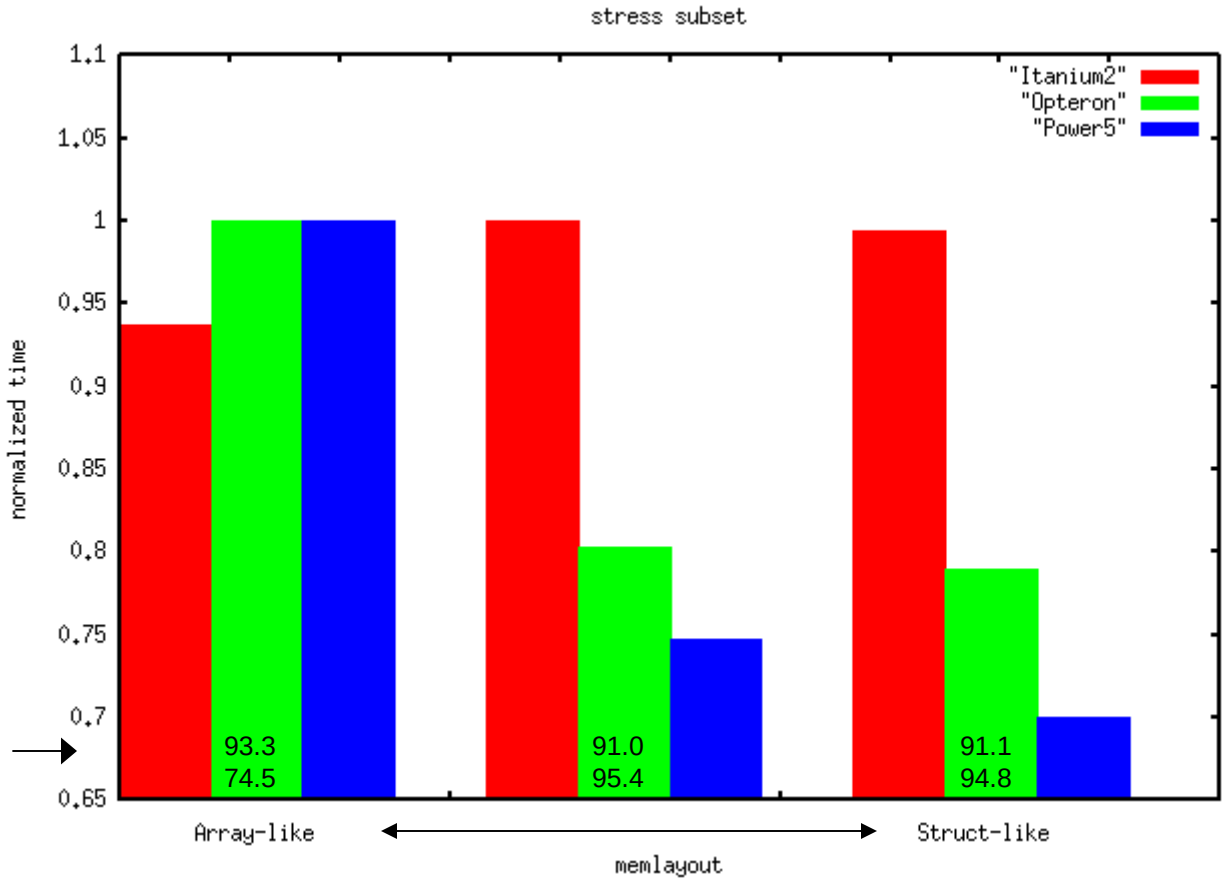
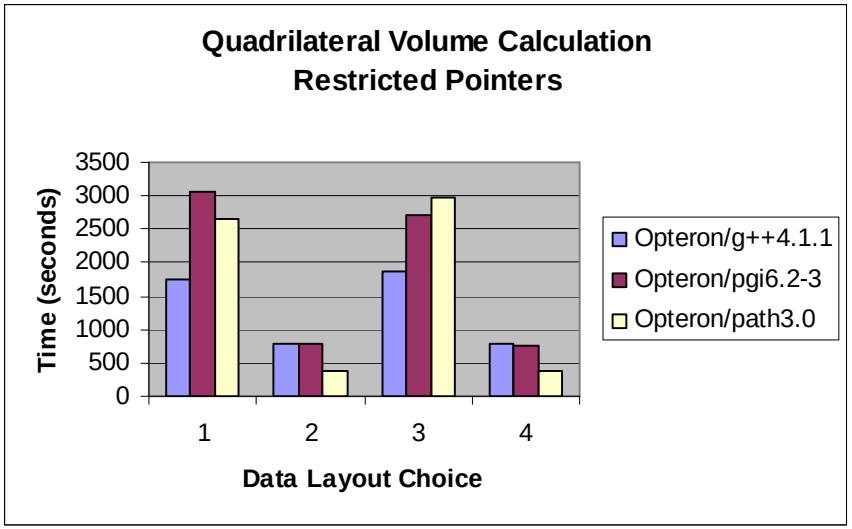
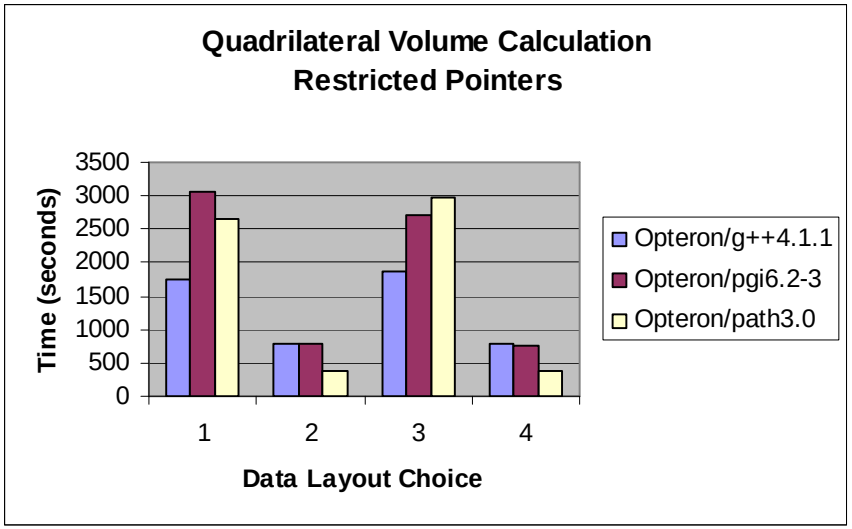
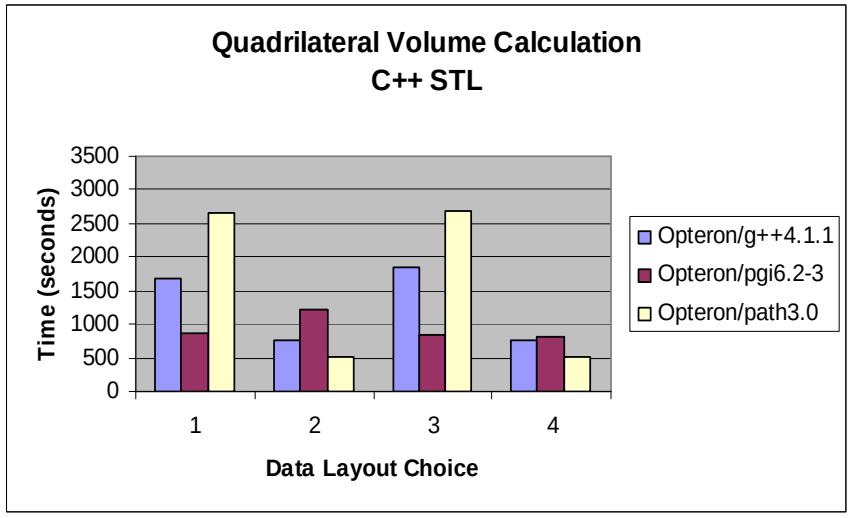
  deltz[index] += quarterDelta * (vnew[index] + v[index]) *
    (    dxx[index] * (sxx[index]  + newSxx[i])  +    dyy[index] * (syy[index]  + newSyy[i]) +
         dzz[index] * (szz         + newSzz[i]) +
     2.*dxy[index] * (txy[index]   + newTxy[i]) + 2.*dxz[index] * (txz[index]  + newTxz[i]) +
     2.*dyz[index] * (tyz[index]   + newTyz[i]) ) ;

  delts[i] += quarterDelta * (vnew[index] + v[index]) *
    (    dxx[index] * sxx[index]  +    dyy[index] * syy[index] +      dzz[index] * szz  +
     2.*dxy[index] * txy[index] + 2.*dxz[index] * txz[index]  +  2.*dyz[index] * tyz[index] ) ;
}
```

Here, each field variable occupies a separate array

Stress-Strain Work Example – Struct-Like Layout

```
for (int i = 0 ; i < material_length ; i++){
   int index = material_map[i];
   double szz = - elem[index].sxx – elem[index].syy ;

   elem[index].deltz += quarterDelta * (elem[index].vnew + elem[index].v) *
     (    elem[index].dxx * (elem[index].sxx + materialElem[i].newSxx)  +
          elem[index].dyy * (elem[index].syy + materialElem[i].newSyy)  +
          elem[index].dzz * (                  szz + materialElem[i].newSzz) +
      2.*elem[index].dxy * (elem[index].txy + materialElem[i].newTxy) +
      2.*elem[index].dxz * (elem[index].txz + materialElem[i].newTxz) +
      2.*elem[index].dyz * (elem[index].tyz + materialElem[i].newTyz) ) ;

   materialElem[i].delts += quarterDelta * (elem[index].vnew + elem[index].v) *
     (    elem[index].dxx * elem[index].sxx  +     elem[index].dyy * elem[index].syy +
          elem[index].dzz * szz                  + 2.*elem[index].dxy * elem[index].txy +
      2.*elem[index].dxz * elem[index].txz  + 2.*elem[index].dyz * elem[index].tyz ) ;
 }
```

Here, there are two contexts – mesh elements and material elements

Stress-Strain Work Example – Clustered-Struct Layout

```
for (int i = 0 ; i < material_length ; i++){
    int index = material_map[i];
    double szz = - stress[index].sxx – stress[index].syy ;

    deltz[index] += quarterDelta * (volume[index].vnew + volume[index].v) *
      (    deform[index].dxx * (stress[index].sxx + materialStress[i].newSxx)  +
           deform[index].dyy * (stress[index].syy + materialStress[i].newSyy)  +
           deform[index].dzz * (                    szz + materialStress[i].newSzz) +
       2.*deform[index].dxy * (stress[index].txy + materialStress[i].newTxy) +
       2.*deform[index].dxz * (stress[index].txz + materialStress[i].newTxz) +
       2.*deform[index].dyz * (stress[index].tyz + materialStress[i].newTyz) ) ;

    delts[i] += quarterDelta * (volume[index].vnew + volume[index].v) *
      (    deform[index].dxx * stress[index].sxx  +     deform[index].dyy * stress[index].syy +
           deform[index].dzz * szz                    + 2.*deform[index].dxy * stress[index].txy +
       2.*deform[index].dxz * stress[index].txz  + 2.*deform[index].dyz * stress[index].tyz ) ;
}
```

Here, contexts are created for each tightly bound group of field arrays

Stress-Strain Work Example – Performance



Cache Hit $\frac{L1}{L2}$ % →

Worse

Better

A mesh of 12000 elements contains two sparse material subsets of 8000 and 4000 elements. The 8000 element subset is evaluated

Stress-Strain Work Example – Cache Performance

	Opteron Hardware Counters L1 Cache		
Data Layout	Hit Count	Miss Count	Hit Ratio
Array-Like	3955732080	286239697	93.3%
Intermediate	2842569424	281404535	91.0%
Struct-Like	2769568352	273753504	91.1%

- Some applications/architectures optimize best with struct-like data layouts due to reduced *register pressure* or better use of *prefetch streams*

Second Example – Quadrilateral Volume

- An unstructured mesh is created for quadrilaterals
  - Lattice of nodes stored as X and Y coordinate arrays
  - Quadrilateral shape defined by four arrays of nodal indices
- Wall clock run time is measured while varying
  - Compilers
  - Data representations (restricted pointers vs. STL)
  - Data Layouts
    - Separate coordinate and shape contexts
    - Switch between Array-Like and Struct-Like layout for each context

Quadrilateral Volume Example – Performance



GNU sees good optimizations for the first and third layout, while PathScale sees good optimizations for the second and fourth.

Quadrilateral Volume Example – Performance





GNU sees good optimizations for the first and third layout, while PathScale sees good optimizations for the second and fourth.

PGI sees more optimizations when using the STL. Note that Pathscale runs 25% slower when using the STL for data layouts number two and four.

Struct-Like Layouts Are Not Optimal For All Architectures

- An x86 SSE enabled processor can optimize well with unaliased aligned array-like data
  - ```
    double *x = new double[10000] ;
    double *y = new double[10000] ;
    double *z = new double[10000] ;
    ```
  - Additional compiler directives are needed throughout the source code to indicate pointers are aligned
    ```

Memory Alignment Is Important For Many Architectures

BG/L memory throughput: a[i] = b[i] + ss*c[i]

Array Size	Unaligned(MB/s)	Aligned(MB/s)
100	3040	6300
1000	3340	8270
10000	1290	3720
100000	1290	3720
500000	1290	1830
1000000	1280	1440

Results: Norris, Hartono, Gropp

Compiler Directives

- Memory Alignment
  - Library calls such as posix_memalign()
  - Compile line options such as –Mcache_align
  - Compiler directives such as
    - __alignx()
    - _declspec(align())
    - __attribute(align())
    - __assume_aligned()
- Alias control
  - For C/C++ use restrict or __restrict__

Roadblocks to Data Layout Flexibility

- Users usually must rewrite their software to switch between Array-Like and Struct-Like data layouts or to take advantage of compiler directives
  - This makes it difficult to adapt software to compensate for performance idiosyncrasies of different compilers or memory subsystems
  - Software ends up being tuned for a specific hardware platform and compiler environment

- Dynamic Memory Management is often supported as a library rather than an integral part of the compiler
  - Compiler cannot generate aggressive optimizations due to incomplete knowledge of data layout, memory alignment, and inter-relations among heap pointers

TALC

- TALC is a source-to-source translator that allows users to direct compiler optimizations through the use of a schema file
- The schema file provides a higher level of type information about the problem being solved
- This enables a tight coordination between run-time memory allocation and compile-time code generation, which are currently somewhat disjoint

TALC – Allowing User Directed Compiler Optimizations

- The Schema file contains high level information about data layouts

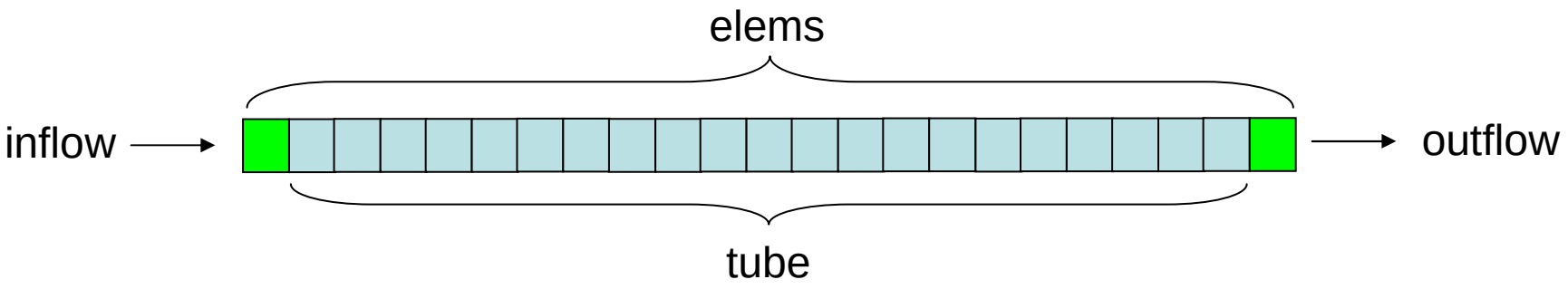
Quadrilateral Schema 1

```
View nodes
  Field x
  Field y
View

View elems
  Relation:nodes n1 n2 n3 n4
View
```

Quadrilateral Schema 2

```
View nodes
  Field x y
View

View elems
  Relation:nodes n1 n2 n3 n4
View
```

TALC Schema



Shock Tube Schema

```
View mesh
  View elems
    Field mass momentum energy
    Field pressure
    View tube
      Relation:faces upWindFace downWindFace
    View
  View

  View faces
    Field flux0 flux1 flux2
    Realtion:elems upWindElem downWindElem
  View
View
```

TALC

- In addition to controlling data layouts via a schema file, source-to-source translation allows us to
  - Align variables when they are allocated on heap
  - Apply machine specific compiler directives to indicate cache alignment and alias restriction
- Features that allow this to work for us
  - Consistent naming of Field arrays and contexts
  - Hierarchical nature of context allocation already in place in many of our scientific codes
  - Intimate familiarity with the structure of our codes

Potential Roadblocks

- Libraries
  - Most libraries expect passed arrays to have a specific memory layout (i.e. stride one array)
  - Even if compiling library source code, the user would need to understand the structure of the library software to create an appropriate schema
- I/O
  - Since many I/O operations are implemented using libraries, the same problem applies as above.
  - A library like MPI that provides a memory layout interface may be automatically transformable

Future Work

- Demonstration of Rapidmind backend
  - Will work on select loops at first, low performance
- Full thread support
  - Demonstration capability is already there
- Structured Indexsets

Schema

```
View  VecSpace:row:col
  Field       A
  Field:row   y
  Field:col   x
View
```

```
MVmul(is *vecSpace, PntrR y, A, x) {
  while(vecSpace->(“row”)) {
    y = 0.0 ;
    while(vecSpace->(“col”)) {
      y += A*x ;
    }
  }
}
```

Conclusion

- A diversity of hardware architectures are being introduced simultaneously (Multi-core, NUMA, GPGPU/vector coprocessors)
- A low-impact change in our programming model may provide a unified way of running effectively on a diversity of system architectures
- A data-layout compiler has been written to explore this issue using the ROSE source-to-source translator